Statement for the Nevada Test Site and Off-Site Locations in the State of Nevada (DIRS 101811-DOE 1996, pp. 4-124 to 4-126). Section 3.1.4.2.2 discusses radiological parameters, including results from regional sample locations.

3.1.4.2.2 *Groundwater at Yucca Mountain*

Groundwater at Yucca Mountain occurs in an unsaturated zone and a saturated zone. This section describes these zones and the characteristics of the groundwater in them.

SUBSURFACE FORMATIONS CONTAINING WATER

Unsaturated zone: The zone of soil or rock between the land surface and the *water table*.

Saturated zone: The region below the *water table* where rock pores and *fractures* are completely saturated with *groundwater*.

Perched water bodies: Saturated lenses (thin layers of water) surrounded by unsaturated conditions.

Unsaturated Zone

Water Occurrence. The unsaturated zone at Yucca Mountain extends down from the crest of the mountain about 750 meters (2,500 feet) to the water table (the upper surface of the saturated zone) (DIRS 151945-CRWMS M&O 2000, p. 8.1-1). The primary emplacement area (the upper block) of the proposed repository would be in the unsaturated zone, at least 160 and up to 400 meters (530 up to 1,300 feet) above the present water table (DIRS 151945-CRWMS M&O 2000, p. 9.4-1). The excavation of the Exploratory Studies Facility, including the Enhanced Characterization of the Repository Block *Cross-Drift*, involved more than 11 kilometers (8.4 miles) of tunnels and testing alcoves. Throughout this excavation, only one fracture was observed to be moist (DIRS 154565-Levich et al. 2000, p. 404); there was no active flow of water. Boreholes in the unsaturated zone identified water in the rock matrix, along faults and other fractures, and in isolated saturated zones of *perched water* (DIRS 151945-CRWMS M&O 2000, p. 8.5-1) (Figure 3-16). The water found in the pores of the rock matrix is chemically different from water found in fractures, perched water, or water in the saturated zone (DIRS 151945-CRWMS M&O 2000, pp. 8.6-1 and 8.6-2). Perched water in Yucca Mountain occurs where fractured rock overlies rock of low permeability such as unfractured rock, and upslope from faults where permeable or fractured rock lies against less permeable rock and fault fill material. Perched water bodies occur approximately 100 to 200 meters (330 to 660 feet) below the proposed repository horizon near the base of the Topopah Spring welded tuff unit (DIRS 151945-CRWMS M&O 2000, p. 8.5-10) (Figure 3-16). Water flow along fractures probably is responsible for recharging the perched water bodies. The apparent age of the perched water based on carbon-14 dating shows residence times of 3,500 to 11,000 years (DIRS 151945-CRWMS M&O 2000, p. 8.6-3). Although there are limitations in the use of carbon-14 dating on water (such as knowing the initial activity of carbon-14, estimating sources of losses or gains, and adjusting for postnuclear age contributions), the perched water is believed to be too recent to be an accumulation of pore water from the rock matrix. Water chemistry data (discussed below) that show the perched water with different characteristics than the pore water provide additional, possibly stronger, evidence that pore water does not contribute significantly to the perched water. To learn how recently recharge might have occurred, these dating efforts also looked for the presence of tritium, which would indicate contributions from water affected by atmospheric nuclear weapons tests (after 1952). The results indicate that if tritium has reached the perched water bodies, it is in quantities too small for reliable detection (DIRS 151945-CRWMS M&O 2000, p. 5.3-30).

Hydrologic Properties of Rock. The unsaturated zone at Yucca Mountain consists of small areas of alluvium (clay, mud, sand, silt, gravel, and other detrital matter deposited by running water) and colluvium (unconsolidated slope deposits) at the surface underlain by volcanic rocks, mainly fragmented

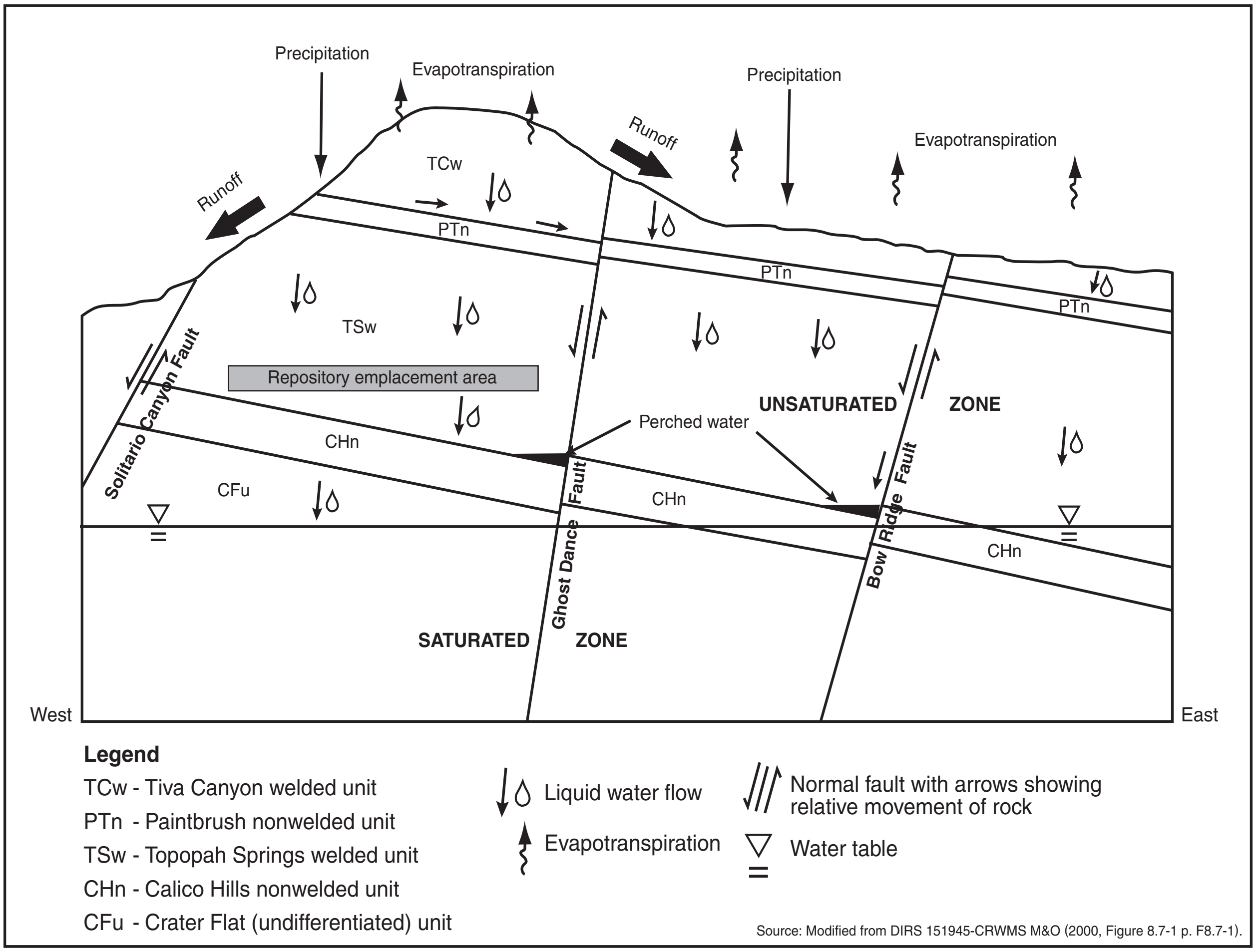


Figure 3-16. Conceptual model of water flow at Yucca Mountain.

materials called tuffs that have varying degrees of welding (DIRS 151945-CRWMS M&O 2000, p. 8.1-1). The hydrologic properties of tuffs vary widely. Some layers of tuff are welded and have low matrix porosities, but many contain fractures that allow water to flow more quickly than through the rock. Other layers, such as nonwelded and bedded tuff, have high matrix porosities but few fractures (DIRS 151945-CRWMS M&O 2000, p. 8.9-2). Some layers have many small hollow bubble-like structures (called lithophysae) that tend to reduce water flow in the unsaturated zone.

Rock units defined by a set of hydrologic properties do not necessarily correspond to rock units defined by geologic properties and characteristics. For geologic studies, rocks are generally divided on the basis of characteristics that reflect the rock origin and manner of deposition. Hydrogeologic units, on the other hand, reflect the manner in which water moves through the rock. A stratigraphic unit and a hydrogeologic unit commonly do not represent the same layer of rock. For example, a rock *stratum* classified as a single stratigraphic unit based on *lithology* or chronology, such as a tuff generated by a volcanic event, can be divided into separate hydrographic units based on hydrologic properties. Further, because the physical processes of water movement are very different under unsaturated conditions than under saturated conditions, the hydrogeologic units defined in the unsaturated zone can differ from those defined when the same rock sequence is saturated. Figure 3-17 shows the relationship between the stratigraphic units discussed in Section 3.1.3 and the hydrogeologic units discussed in this section, including the aquifers and confining units that make up the area's groundwater system. Table 3-13 lists the hydrogeologic units in the unsaturated zone at Yucca Mountain.

Era	Geologic Age	Stratigraphic unit	Approximate range of thickness (meters)	Hydrogelogic units Unsaturated	Saturated	Comments
Cenozoic Era	Quaternary and Tertiary Periods	Alluvium, colluvium, eolian deposits, spring deposits, basalt lavas, lacustrine deposits, playa deposits	**0-130**	QAL, alluvium	QTa, Valley-fill aquifer; QTc, valley-fill confining unit	QAL restricted to stream channels on Yucca Mountain; QTa occurs mainly in Amargosa Desert; major water-supply source; subsurface extent of the QTc unit is not well established
	Tertiary Period	Timber Mountain Group Rainier Mesa Tuff				Minor erosional remnants at Yucca Mountain
		Paintbrush Group Tiva Canyon Tuff	0-150	TCw Tiva Canyon welded unit		Mainly densely welded; caprock on Yucca Mountain; not known in saturated zone at or near Yucca Mountain
		(bedded tuff) Yucca Mountain Tuff Pah Canyon Tuff	20-100	PTn Paintbrush nonwelded unit		Includes bedded and nonwelded tuffs between basal part of Tiva Canyon Tuff and upper part of Topopah Spring Tuff
		Topopah Spring Tuff (vitrophyre and non-welded tuffs at base)	290-360	TSw Topopah Spring welded unit	uva, Upper volcanic aquifer	About 300 meters of densely welded tuff in unsaturated zone; host rock for repository; in saturated zone where downfaulted to east, south, and west of site
		Calico Hills Formation	150-500	CHn Calico Hills nonwelded unit	uvc, Upper volcanic confining unit	Mainly nonwelded tuff, with thin rhyolite lavas in northern site area; varies from vitric in southwest site area to zeolitic where near or below water table
		Crater Flat Group Prow Pass Tuff Bullfrog Tuff Tram Tuff	200-500	CFu Crater Flat undifferentiated unit	mva Middle volcanic aquifer	Small occurrence in unsaturated zone; widespread in saturated zone; variably welded ash-flow tuffs and rhyolite lavas; commonly zeolitized; most permeable zones are fracture-controlled
		Unnamed flow breccia Lithic Ridge Tuff	400-1,000		mvc, Middle volcanic confining unit	Nonwelded tuff, pervasively zeolitized
		Volcanics of Big Dome			lva, Lower volcanic aquifer	Lava flows and welded tuff; not known at Yucca Mountain
	(Lower Tertiary?)	Older volcanics			lvc, Lower volcanic confining unit	Nonwelded tuff, pervasively zeolitized; tuffaceous sediments in lower part
Paleozoic Era	Permian/ Pennsylvanian Periods	Bird Spring Formation Tippipah Limestone	1,000 ±		uca, Upper carbonate aquifer	Limited distribution in saturated zone north and east of Yucca Mountain
	Mississipian/ Devonian Periods	Eleana Formation (Chainman Shale)	2,500 ±		ecu, Eleana confining unit	Argillite (mudstone) and siltstone; occurrence inferred beneath volcanics of northern Yucca Mountain
	Devonian Silurian Ordovician Cambrian Periods	Devils Gate Limestone, Nevada Formation, Ely Springs Dolomite, Eureka Quartzite, Pogonip Group, Nopah Formation, Dunderberg Shale, Bonanza King Formation, Upper Carrara Formation	8,500 ±		lca, Lower carbonate aquifer	Mainly limestone and dolomite with relatively thin shales and quartzites; major regional aquifer, more than 5 kilometers (3.1 miles) thick
		Lower Carrara Formation			qcu, Precambrian confining unit	Dolomite, shale
	Proterozoic (Upper Precambrian)	Proterozoic rocks				Quartzite, slate, marble; fractures commonly healed by mineralization

Source: Modified from DIRS 151945-CRWMS M&O (2000, Tables T9.3-1 and T9.3-2, Thickness date: Figures 4.5-3 and 4.5-4, pp. F4.5-3 and F4.5-4, and Table 9.2-2, pp. T9.2-2 and T9.2-3).

Figure 3-17. Correlation of generalized stratigraphy with unsaturated and saturated hydrogeologic units in the Yucca Mountain vicinity.

Table 3-13. Hydrogeologic units in the unsaturated zone at Yucca Mountain.[a]

Unit and characteristics[b]	Thickness (meters)[c]
Quaternary alluvium/colluvium Unconsolidated stream deposits beneath valleys and loose slump deposits beneath slopes; porosity and permeability medium to high.	0 - 130
Tiva Canyon welded unit (TCw) Mainly pyroclastic flow tuffs; porosity typically 10 to 30 percent; saturation commonly 40 to 90 percent.	0 - 150
Paintbrush nonwelded unit (PTn) Includes the Yucca Mountain and Pah Canyon Tuffs and uppermost part of the welded Topopah Spring Tuff; porosity generally high, 30 to 50 percent; matrix saturation, 40 to 70 percent.	20 - 100
Topopah Spring welded unit (TSw) Mainly devitrified ash flow tuff; porosity generally low, less than 20 percent, but up to 40 percent in glassy zones; matrix saturation generally greater than 50 percent, commonly greater than 80 percent.	290 - 360
Calico Hills nonwelded unit (CHn) Made up of four subunits, the lower three of which contain zeolites; the unit also includes Prow Pass Tuff (pyroclastic flow) of the Crater Flat Group; porosity generally 20 to 40 percent; matrix saturation 30 to 90 percent, commonly near 100 percent in zeolitic zones.	150 - 500
Crater Flat undifferentiated unit (CFu) Consists of welded Bullfrog Tuff (stratigraphically above) and nonwelded Tram Tuff (stratigraphically below); is below water table in much of the area, but is unsaturated beneath western part of Yucca Mountain; Bullfrog Tuff has low porosity, less than 20 percent, and high matrix saturation, close to 100 percent; Tram Tuff has porosity 20 to 40 percent; and high matrix saturation.	200 - 500

a. Source: DIRS 151945-CRWMS M&O (2000; Units and Descriptions - pp. 4.5-18 to 4.5-33 and 8.3-6 to 8.3-10; Porosity and Saturation - Figures 8.3-1 and 8.3-2, pp. F8.3-1 and F8.3-2, and Table 8.3-2, p. T8.3-3; and Thickness - Figures 4.5-3 and 4.5-4, pp. F4.5-3 and F4.5-4).
b. Letters in parentheses are used in Figures 3-16 and 3-17
c. To convert meters to feet, multiply by 3.2808.

Water Source and Movement. When precipitation falls on Yucca Mountain, part leaves as runoff, part evaporates, and part infiltrates the ground. Some of the water that infiltrates the ground eventually evaporates in the arid climate or passes to plants; the remainder percolates into the ground as infiltration.

Some of the infiltration remains at shallow levels, some eventually rises to the surface as vapor, and some (called *net infiltration*) moves deeper into the unsaturated zone. The estimated net infiltration for the current climate is 3.6 millimeters (0.1 inch) per year in a study area of about 120 square kilometers (48 square miles) that includes Yucca Mountain and 4.7 millimeters (0.2 inch) per year in the potential repository area (DIRS 151945-CRWMS M&O 2000, Tables 8.2-7 and 8.2-9, pp. T8.2-6 and T8.2-7). These are estimates of average net infiltration for fairly large surface areas. Because of the arid climate, the sporadic nature of storms, and the variation in topography, the actual amount of annual infiltration varies widely from year to year and across the area. Yucca Mountain Project studies have shown that net infiltration varies over segments of the larger areas based, in part, on the amount of unconsolidated material present. The estimated net infiltration over the study area ranges from zero where alluvium is more than 6 meters (20 feet) thick to 8 centimeters (3 inches) and more where thin alluvium overlies highly permeable bedrock (DIRS 100147-Flint, Hevesi, and Flint 1996, p. 91). On a year-to-year basis, the average net infiltration over the repository might range from 0.4 to 11.6 millimeters (0.02 to 0.5 inch) (DIRS 151945-CRWMS M&O 2000, Table 8.2-9, p. T8.2-7).

Groundwater movement in the unsaturated zone at Yucca Mountain occurs in the pore space (matrix) of rock units and along faults and fractures of rock units. Water movement through the pore space of rock units is a relatively slow (or stagnant) process compared with flow through faults and fractures (DIRS 151945-CRWMS M&O 2000, p. 8.9-10). Water movement through faults and fractures is believed to be episodic in nature (occurring at discrete times related to periods of high surface infiltration), is capable of traveling rapidly through rock units, and is the likely source of perched water in the unsaturated zone (DIRS 151945-CRWMS M&O 2000, pp. 8.9-3 to 8.9-6).

The characteristics of groundwater movement through specific rock units differ based on their hydrogeologic properties (DIRS 151945-CRWMS M&O 2000, pp. 8.9-2 to 8.9-3). Water that infiltrates into the Tiva Canyon welded unit can often be transported rapidly through fractures as deep as the underlying Paintbrush nonwelded unit. Due to its high porosity and low fracture density, the Paintbrush unit tends to slow the downward velocity of water flow dramatically in relation to highly fractured units such as the Tiva Canyon unit. However, isotopic (chlorine-36) analysis has identified isolated pathways that provide relatively rapid water movement for very small amounts of water (DIRS 151945-CRWMS M&O 2000, p. 8.12-16) through the Paintbrush nonwelded unit to the top of the underlying Topopah Springs welded unit where, due to increased fracturing, it has the potential to travel quickly through the unit.

DOE has used the ratio of chlorine-36 (a naturally occurring *isotope*) to total chlorine to determine where and when moisture has moved in the unsaturated zone at Yucca Mountain. High enough chlorine-36 ratios indicate waters exposed to very small amounts of fallout associated with above-ground nuclear weapons testing (called bomb-pulse water). The methodology used in these studies is complicated and is still under investigation; however, findings thus far have been valuable in reaching certain conclusions.

CHLORINE-36 STUDIES

These studies use the fact that a very small portion of chlorine in the atmosphere consists of the radioactive isotope chlorine-36. The production of chlorine-36 (caused in part by interactions between argon molecules and high-energy protons and neutrons in the atmosphere) is sufficiently balanced with the rate of its removal as atmospheric fallout that the ratio of chlorine-36 to stable chlorine (chlorine-35 and -37) at any given location remains fairly constant in atmospheric salts deposited on land, such as that dissolved in rainwater. Once chlorine is isolated from the surface environment (as when dissolved in water percolating down through the soil and subsurface rocks), subsequent changes in the chlorine-36-to-total-chlorine ratio can be attributed to decay of the chlorine-36 (DIRS 101005-Levy et al. 1997, p. 2) (that is, if the residence times are long enough in relation to the 301,000-year half-life of this radionuclide). Measuring the chlorine-36-to-total-chlorine ratio in underground water or in residues it leaves behind, and knowing what the ratio was at the time of recharge provides a means of estimating the age of the water. In reality, slight variations over time in the atmospheric ratio and the potential for some minor production of chlorine-36 in the subsurface has made the use of this technique for water dating difficult, and its use is still under investigation. However, the atmospheric ratio of chlorine-36 to total chlorine has increased by orders of magnitude as a result of above-ground nuclear testing during the past 50 years. As a consequence, the technique has been very successful in tracing underground water or water residues that originated at the surface within the past 50 years, with the so-called *bomb-pulse signal* indicating very young water.

Chlorine-36 analyses at Yucca Mountain have identified locations where water has moved fairly rapidly (in several decades) from the surface to the depth of the proposed repository and also where it has moved very slowly (thousands to tens of thousands of years). The chlorine-36 studies included one study that collected 247 rock samples along the 8-kilometer (5-mile) Exploratory Studies Facility tunnel (DIRS 151945-CRWMS M&O 2000, p. 8.6-3). About 70 percent of the samples were from areas thought to be more likely to show evidence of rapid water movement [that is, areas of broken rock such as faults, fractures, or breccia zones (areas where rock composed of fragments of older rocks melded together)] (DIRS 100144-Fabryka-Martin et al. 1997, p. 4-13).

Most of the samples (77 percent) had ratios that were ambiguous in that they fell within the range over which the chlorine-36-to-total-chlorine ratio has varied over the last 30,000 years or more (DIRS 100144-Fabryka-Martin et al. 1997, p. 3-1). Results of these samples indicate that the groundwater travel times from the surface to the repository depth in most areas probably are thousands to tens of thousands of years. This is because there is little evidence for measurable radioactive decay of the chlorine-36 signal in the subsurface. However, a few samples indicated ratios low enough to suggest the possible presence of zones of relatively old or stagnant water.

About 13 percent of the samples (31 samples) had high enough chlorine-36-to-total-chlorine ratios to indicate the water originated from precipitation occurring in the past 50 years (that is, nuclear age precipitation) (DIRS 151945-CRWMS M&O 2000, p. 8.6-3). Locations where bomb-pulse water occurred were correlated with the physical conditions in the mountain and on the surface that could lead to, or otherwise affect, the findings. The conclusion to date of these ongoing studies is that relatively fast transport of water through the mountain is controlled by the following factors (DIRS 104878-CRWMS M&O 1998, p. 3-2):

- The presence of a continuous fracture path from the surface: The limiting factor is a fracture or fault cutting the Paintbrush nonwelded bedded tuffs (PTn) hydrogeologic unit (this prominent unit is above the repository horizon; see Figure 3-16 and Table 3-13). Fracture pathways are normally available in the welded portions of the overlying Tiva Canyon and underlying Topopah Spring units. This is consistent with hydrologic modeling of *percolation* through this nonwelded bedded tuff, which indicates that there must be fracture pathways due to faulting or other disturbances for water to travel through this unit in 50 years or less. Section 3.1.3 discusses fault locations inside Yucca Mountain.

- The magnitude of surface infiltration: There must be enough infiltration to sustain a small component of flow along the connected fracture pathway.

- The residence time of water in the soil cover: This time must be less than 50 years; to achieve this, the depth of the soil overlying the fracture pathway must be less than an estimated 3 meters (10 feet).

Several important factors affect a discussion of chlorine-36 studies. Ratios of naturally occurring radioactive chlorine-36 to the other isotopes of chlorine are on the order of one chlorine-36 atom to approximately two trillion (2,000,000,000,000) other chlorine atoms. Samples designated as showing evidence of elevated, “bomb-pulse” chlorine-36 still have exceedingly minute amounts of this isotope, containing only two to eight times the amount that occurs naturally. The scale of these measurements and the significance being placed on them makes understanding the sources of chlorine-36 in the underground environment and the intricacies of the analytical procedures extremely important. To ensure the correct interpretation of this subtle chemical signal (that is, of elevated amounts of chlorine-36), studies are underway to determine whether independent laboratories and related isotopic studies corroborate the findings.

Water percolating to the depth of the repository and beyond is affected not only by fractures but also by the nature of the hydrogeologic units it encounters. Pressure testing in boreholes indicates that fractures in the Topopah Spring tuff (the rock unit in which DOE would build the repository) are very permeable and extensively interconnected (DIRS 151945-CRWMS M&O 2000, p. 8.12-5). Below the repository level, low-permeability zones impede the vertical flow of water in the Calico Hills nonwelded unit (which includes the basal part of the Topopah Springs Tuff, Figure 3-17), forming perched water bodies (DIRS 151945-CRWMS M&O 2000, pp. 8.9-5 and 8.9-6). The primary source of the perched water is water traveling down along faults and fractures. In the dipping or sloped strata beneath Yucca Mountain, perched water bodies require vertical impediments such as fault zones where less permeable rock and fault-gouge material block the lateral flow of water (Figure 3-16). If these conditions do not exist at the fault zone, the fault can provide a downward pathway. Even in cases where fault zones are barriers to lateral water flow, they can be very permeable to gas and moisture flow along the fault plane and permit the rapid vertical flow of water from the land surface to great depth. Studies of heat flux above and below the perched water zone appear to indicate more water percolation above the perched water than below (DIRS 100627-Bodvarsson and Bandurraga 1996, p. 21). This is consistent with the concept that some of the water moves laterally on top of the low-permeability zone before it resumes its downward course to the saturated zone.

DOE has recently undertaken development of what is termed an "expected-case" model of groundwater flow in the unsaturated zone as reported in DIRS 156609-BSC (2001, all). One of the objectives of this effort was to evaluate the impact of the conservatism in the Total System Performance Assessment (TSPA) modeling (see Chapter 5 and Appendix I). The study examined the flow and transport models used in the TSPA effort to identify areas where conservatism could be reduced and uncertainty better characterized. The result is a model of unsaturated zone flow that DOE believes is more realistic than the conservative one. The expected-case model was run under several varying conditions, including runs assuming a nonsorbing tracer, which moves like water, was released at the level of the proposed repository. The results indicate it would take in the range of 7,000 to 8,000 years for 50 percent of the tracer to reach the underlying water table (DIRS 156609-BSC 2001, Figure 6.5-29, p. 183). Some of the tracer would find its way to faster pathways to the water table; some would take longer to travel the distance. Several different conceptual models of groundwater movement in the unsaturated zone were integrated into runs of the numerical mode. DOE believes the most likely case, as described here, presents an estimate of groundwater travel time from the proposed repository to the water table that is a reasonable representation of what occurs in the natural setting.

Unsaturated Zone Groundwater Quality. DOE has analyzed water from the unsaturated zone, both pore water from the rock matrix and perched water, to obtain information on the mechanisms of recharge and the amount of connection between the two. The preceding sections discuss some of the relevant findings.

Table 3-14 summarizes the chemical composition of perched and pore water samples from the vicinity of Yucca Mountain.

Table 3-14. Water chemistry of perched and pore water samples in the vicinity of Yucca Mountain.[a]

	Ranges of chemical composition	
Constituent	Perched	Pore
pH	7.6 - 8.7	7.7 - 8.4
Total dissolved solids (milligrams per liter)	140 - 330	320 - 360
Calcium (milligrams per liter)	2.9 - 45	1.1 - 62
Magnesium (milligrams per liter)	0 - 4.1	0 - 4.5
Potassium (milligrams per liter)	1.7 - 10	N/A[b]
Sodium (milligrams per liter)	34 - 98	49 - 140
Bicarbonate (milligrams per liter)	110 - 220	170 - 230
Chloride (milligrams per liter)	4.1 - 16	26 - 90
Bromide (milligrams per liter)	0 - 0.41	0
Nitrate (milligrams per liter)	0 - 34	11 - 17
Sulfate (milligrams per liter)	4 - 220	14 - 45

a. Source: DIRS 104951-Striffler et al. (1996, Table 2).
b. N/A = not available.

The smaller concentrations of dissolved minerals, particularly chloride, in perched water in comparison to those in pore water is a primary indicator of differences between the two. This difference in dissolved mineral concentrations indicates that the two types of water do not interact to a large extent and that the perched water reached its current depth with little interaction with rock. This, in turn, provides strong evidence that flow through faults and fractures is the primary source of the perched water (DIRS 151945-CRWMS M&O 2000, p. 5.4-2).

Saturated Zone

Water Occurrence. The saturated zone at Yucca Mountain has three aquifers and two confining units. The aquifers are commonly referred to as the upper volcanic aquifer, the lower volcanic aquifer, and the lower carbonate aquifer. The interlayered aquitards (low permeability units that retard water movement) that separate the aquifers are called the upper volcanic confining unit and the lower volcanic confining unit (see Figure 3-17). The upper volcanic aquifer is composed of the Topopah Spring welded tuff, which occurs in the unsaturated zone near the repository but is present beneath the water table to the east and south of the proposed repository. The upper volcanic confining unit includes the vitrophyre and nonwelded tuffs at the base of the Topopah Spring Tuff, the Calico Hills nonwelded unit, and the uppermost unstructured end of the Prow Pass tuff where they are saturated. The lower volcanic aquifer includes most of the Crater Flat Group, and the lower volcanic confining unit includes the lowermost Crater Flat Group and deeper tuff, lavas, and flow breccias. An upper carbonate aquifer, though regionally important, is not known to occur beneath Yucca Mountain. (The lower volcanic aquifer discussed here corresponds to the middle volcanic aquifer shown in Figure 3-17. The lower volcanic aquifer in Figure 3-17 has not been identified in the area of the proposed repository.)

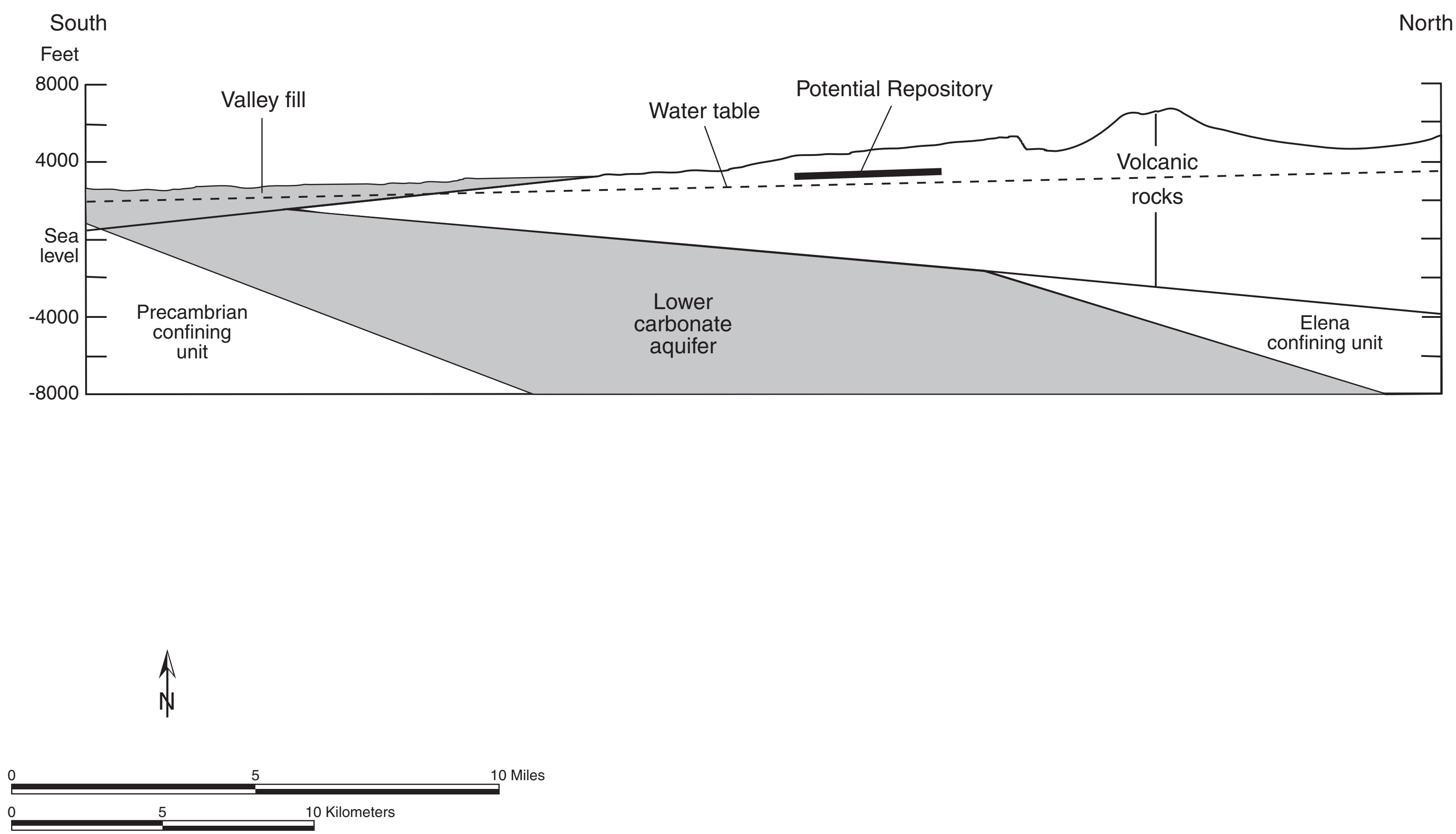
TYPES OF TUFF

Welded tuff results when the volcanic ash is hot enough to melt together and is further compressed by the weight of overlying materials.

Non-welded tuff results when volcanic ash cools in the air sufficiently that it does not melt together, yet later becomes rock through compression.

South of the proposed repository site, downgradient in the groundwater flow path from Yucca Mountain, the Tertiary volcanic rocks (and the volcanic aquifers) pinch out and groundwater moves into the valley-fill sediments of the Amargosa Desert (DIRS 151945-CRWMS M&O 2000, p. 9.3-80). Figure 3-18, which is a generalized hydrogeologic cross-section from Yucca Mountain to the northern portion of the Amargosa Desert, shows the relative positions of these aquifers. In the Amargosa Desert south of Yucca Mountain, the most important source of water is an aquifer formed by valley-fill deposits (DIRS 151945-CRWMS M&O 2000, p. 9.2-23).

The lower carbonate aquifer is more than 1,250 meters (4,100 feet) below the proposed repository horizon (DIRS 151945-CRWMS M&O 2000, Table 9.3-8, p. T9.3-10). This aquifer, which consists of lower Paleozoic carbonate rocks (limestone and dolomite) that have been extensively fractured during many periods of mountain building (see Section 3.1.3), forms a regionally extensive aquifer system through which large amounts of groundwater flow (DIRS 151945-CRWMS M&O 2000, p. 9.2-8). Evidence indicates that water in the lower carbonate aquifer is at least as old as most of the water in the volcanic aquifers (with apparent ages in the range of 10,000 to 20,000 years) (DIRS 151945-CRWMS M&O 2000, pp. 9.2-57 and 9.6-4) and, similarly, was recharged during a wetter and cooler climate (DIRS 151945-CRWMS M&O 2000, p. 9.6-4). Some of the limited carbonate aquifer sample results indicate older water ages (up to 30,000 years), but use of carbon-14 dating on this water has an additional limitation due to the probable contribution of “dead carbon” (nonradioactive) dissolved from the carbonate rock (DIRS 151945-CRWMS M&O 2000, p. 9.2-57).



Source: Modified from DIRS 151945-CRWMS M&O (2000, Figure 9.3-4, p. F9.3-4).

Figure 3-18. Cross section from Northern Yucca Mountain to Northern Amargosa Desert, showing generalized geology and the water table.

Limited data at Yucca Mountain show that the level to which water rises in a well that penetrates the lower carbonate aquifer is about 20 meters (66 feet) higher than the water levels in the overlying volcanic aquifers (DIRS 151945-CRWMS M&O 2000, p. 9.3-34). Four other wells at Yucca Mountain that penetrate as deep as the lower volcanic confining unit (the unit above the carbonate aquifer), show higher potentiometric levels in that unit than in overlying volcanic aquifers. This might be an indication of the upward hydraulic gradient in the carbonate aquifer (DIRS 100465-Luckey et al. 1996, p. 29). One of the wells for the Nye County Early Warning Drilling Program, which is about 19 kilometers (12 miles) south of the repository site, also penetrated the carbonate aquifer and shows it to have an upward gradient. At this location, water in the carbonate aquifer well rises 8 meters (26 feet) higher than the water level in the overlying volcanic aquifer (DIRS 155950-BSC 2001, pp. 12-12 and 12-13, and Figure 12.3.2-1, p. 12F-4). This indicates that, in the vicinity of Yucca Mountain, and in areas to the south, water from the lower carbonate aquifer is pushing up against a confining layer with more force than the water in the upper aquifers is pushing down. This suggests that water in the volcanic aquifers does not flow down into the lower carbonate aquifer at Yucca Mountain because it would be moving against a higher upward pressure and that, if mixing occurs, it would be from carbonate to volcanic and not the reverse.

Paleoclimatic (referring to the climate during a former period of geologic time) studies have identified five wetter and cooler periods in the southern Great Basin during the past 400,000 years (late Pleistocene). These periods occurred 10,000 to 50,000 years ago; 60,000 to 70,000 years ago; 120,000 to 170,000 years ago; 220,000 to 250,000 years ago; and 330,000 to 400,000 years ago. They represent the sequencing of glacial (cooler and wetter) to interglacial (warmer and drier) and back to glacial climates (DIRS 151945-CRWMS M&O 2000, p. 6.3-19). Calcite veins and opal were deposited along fractures during the wetter periods. The calcite and opal coatings have been dated by the uranium series method; the calcites have also been dated by the carbon-14 method. The youngest vein deposits are 16,000 years old (DIRS 151945-CRWMS M&O 2000, p. 6.3-33). During the wetter periods, the estimated regional water table was a maximum of 120 meters (390 feet) above the present level beneath Yucca Mountain during the past million or more years based on mineralogic, isotopic, and discharge deposit data and on hydrologic modeling analysis. The water table could rise by an estimated 50 to 130 meters (160 to 430 feet) from current levels under hypothetical future wetter climate conditions (DIRS 137917-CRWMS M&O 2000, p. 9.4-24). The proposed repository drift layouts would all be well above these historic and possible future maximum water table elevations (see Section 2.1). The *Yucca Mountain Site Description* (DIRS 151945-CRWMS M&O 2000, pp. 6.3-1 to 6.3-39) provides additional information, including supporting evidence, on the timing, magnitude, and character of past climate changes in the Yucca Mountain region.

Several investigators have suggested that the water table in the vicinity of Yucca Mountain has risen dramatically higher than 120 meters (390 feet) above the current level, even reaching the land surface in the past (DIRS 106963-Szymanski 1989, all). If such an event occurred, it would affect the performance of the proposed repository. These concerns originated in the early- to mid-1980s when surface excavations performed as part of site investigations exposed vein-like deposits of calcium carbonate and opaline silica (DIRS 151945-CRWMS M&O 2000, p. 4.4-25). DIRS 106963-Szymanski (1989, all) hypothesized that the carbonate and silica were deposited by hydrothermal fluids, driven to the surface by pressurization of groundwater by earthquakes (a mechanism called *seismic pumping*) or by thermal processes that occurred in the Yucca Mountain vicinity. A number of investigators and groups, including a National Academy of Science panel specifically designated to look at the issue (DIRS 105162-National Research Council 1992, all), have examined the model on which this position is based and have rejected its important aspects (DIRS 100465-Luckey et al. 1996, pp. 76 to 77). The National Research Council panel concluded that the evidence cited as proof of groundwater upwelling in Yucca Mountain and in its vicinity could not reasonably be attributed to that process. In addition, the panel stated its position that the proposed mechanism for upwelling water was inadequate to raise the water table more than a few tens of meters (DIRS 101779-DOE 1998, Volume 1, p. 2-26). Finally, the panel concluded that the carbonate-rich depositions in fractures were formed from surface water from precipitation and surface processes (DIRS 151945-CRWMS M&O 2000, p. 4.4-36).

Another alternative interpretation of past groundwater levels at Yucca Mountain occurs in DIRS 104875-Dublyansky (1998, all). This study involved the examination of tiny pockets of water (known as *fluid inclusions*) trapped in the carbonate-opal veinlets deposited in rock fractures at Yucca Mountain. According to the report, an analysis of samples collected from the Exploratory Studies Facility includes evidence of trace quantities of hydrocarbons and evidence that the fluid inclusions were formed at elevated temperatures. These findings, and others, are used to support the report's conclusion that the carbonate-opal veinlets were caused by warm upwelling water and not by the percolation of surface water. DOE, given the opportunity to review a preliminary version of the report, arranged for review by a group of independent experts, including U.S. Geological Survey personnel and a university expert. This review group did not concur with the conclusion in the report by DIRS 104875-Dublyansky (1998, all), which now contains an appendix with the DOE-arranged review comments and the author's responses. Although DOE disagreed with some of the central scientific conclusions presented in this report, both parties agreed that additional research was needed to resolve the issue. As a result, DOE supported an independent investigation by the University of Nevada at Las Vegas, in which both the U.S. Geological Survey and the State of Nevada were invited to participate. This independent effort to analyze mineral samples from Yucca Mountain is not yet final, but University researchers presented papers on their preliminary findings at a November 2000 meeting of the Geological Society of America. They reported (DIRS 154280-Wilson et al. 2000, all) that evidence was present of fluid inclusions being formed at elevated temperature, but generally in the older (basal) part of the samples. Uranium-lead dating of the minerals in the younger outer surfaces, where there was no such evidence, indicates these minerals began precipitating between 3.8 and 1.9 million years ago. As a result, the study concluded that passage of fluids with elevated temperatures occurred prior to that time.

Opposing viewpoints dealing with the analysis of mineral samples from Yucca Mountain were presented at the same meeting of the Geological Society of America. One paper (DIRS 154790-Pashenko and Dublyansky 2000, all) reiterated the position that the apparent deposition temperatures of fluid inclusions were simply too high to be attributed to descending rainwater. Another (DIRS 154789-Dublyansky 2000, all) pointed to the diversity in the make-up of the mineral deposits as another piece of evidence suggesting a low-temperature hydrothermal (upwelling) origin. DOE and the State of Nevada are continuing to evaluate these and other alternative conceptual models and data interpretations.

Hydrologic Properties of Rock. This section discusses the hydrologic properties of rock in the saturated zone, and specifically the aquifers and confining units at Yucca Mountain. As discussed above, these properties depend in part on whether the rocks are saturated. In general, the amount and speed at which water flows through an aquifer depend chiefly on the transmissivity and effective porosity of the rock. *Transmissivity* is a measure of how much water an aquifer can transfer and is equal to the average hydraulic conductivity of the aquifer multiplied by the thickness of the aquifer that is saturated. *Hydraulic conductivity* is the volume of water moving in an aquifer during a unit of time through a unit of area that is perpendicular to the direction of flow. *Porosity* is the ratio of the rock's void (open) space to its total volume; *effective porosity* is the ratio of interconnected void space to total volume.

Figure 3-19 shows the types of conditions that might exist in gravel and rock aquifers that would make them more or less permeable to water movement. The empty spaces between gravel fragments or in the rock fractures represent the porosity. Although not necessarily representative of conditions at Yucca Mountain, the figure shows that the manner in which void spaces are interconnected, more than their size or quantity, determines how water can move through the material. At Yucca Mountain, conditions are often such that the rock with the highest porosity is also the rock with the fewest fractures (DIRS 151945-CRWMS M&O 2000, p. 9.2-7). Because the void spaces are not interconnected very well, such a high-porosity rock has low transmissivity. Because a large portion of the groundwater flow at Yucca Mountain

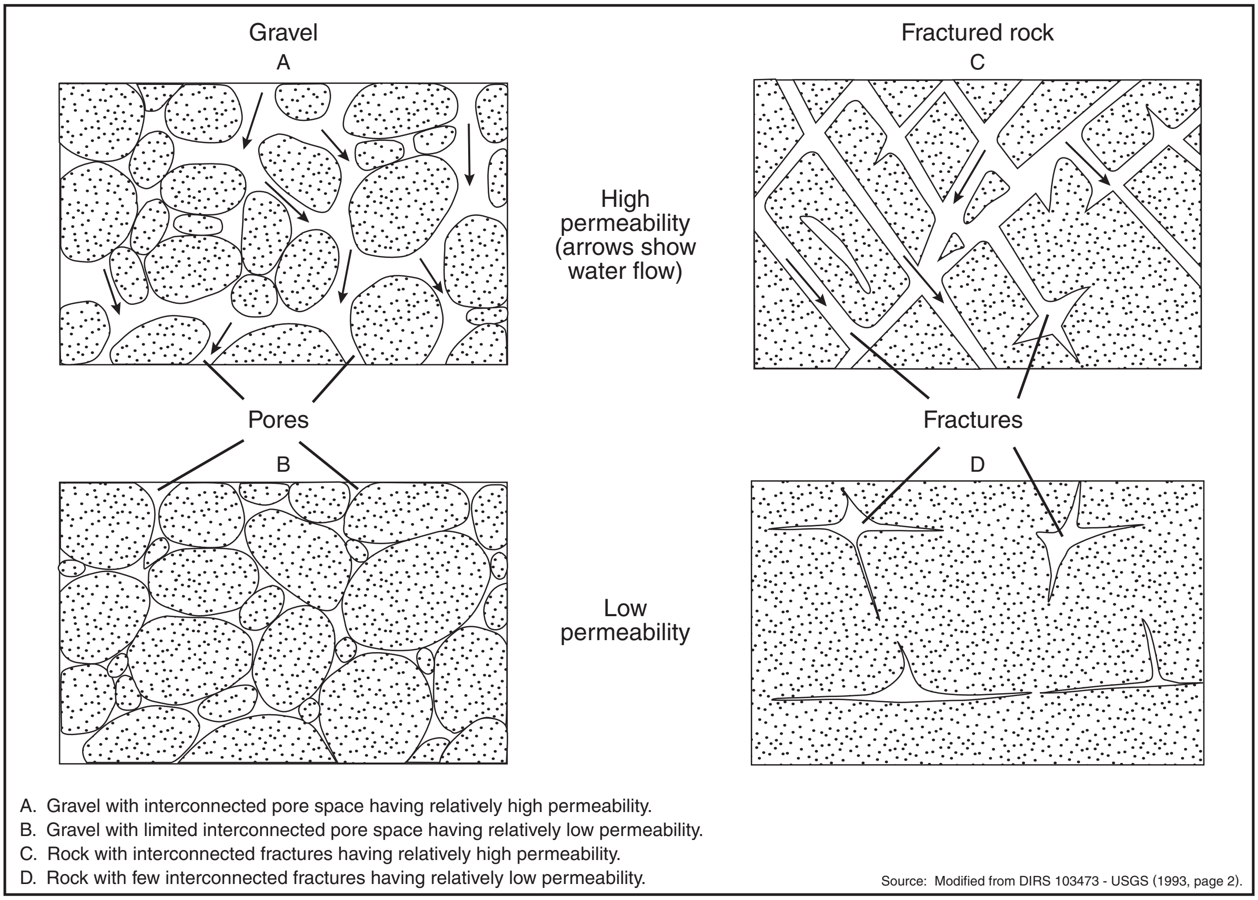


Figure 3-19. Aquifer porosity and effects on permeability.

is probably along fractures, representative transmissivity values are difficult to measure. Measurements can vary greatly depending on the nature of the fractures that happen to be intercepted by the borehole and the location in the borehole at which measurements are made. This is reflected in the wide range of transmissivity values listed in Table 3-15, which also lists the characteristics, thicknesses, apparent hydraulic conductivities, and porosities of the three aquifers and two confining units beneath Yucca Mountain. For the lower carbonate aquifer, the table lists a single transmissivity value because there was only a single test for that unit. Similarly, only one apparent hydraulic conductivity value, which is a measure of the aquifer’s capacity to transport water, is provided for the lower carbonate aquifer unit because it is based on tests in a single well at Yucca Mountain. However, the value is an average of measurements taken from that well. This and the other hydraulic conductivity values are called *apparent* because they are all based on single-borehole tests. Such measurements, which are believed to represent conditions at a limited distance around the well, could vary greatly depending on whether there are water-bearing fractures in the well zone being tested. When such fractures are present, hydraulic properties measured in a single-borehole test probably reflect conditions only in isolated locations rather than in the overall rock matrix in the test zone.

Water Source and Movement. Section 3.1.4.2.1 describes the direction of water movement (Figure 3-15), the nature of the rock through which it moves, and where local recharges to and discharges from the aquifer might occur.

When undisturbed by pumping, groundwater levels at Yucca Mountain have been very stable. A Geological Survey study of water levels over 10 years (1985 to 1995) indicated water levels did not change by season and most water-level fluctuations are probably due to changes in barometric pressure

Table 3-15. Aquifers and confining units in the saturated zone at Yucca Mountain.

Unit	Typical thickness (meters)[a,b,c]	Transmissivity (square meters per day)[d,e]	Apparent hydraulic conductivity (meters per day)[e]	Typical porosity[f,g] (ratio)
Upper volcanic aquifer Densely welded and densely fractured part of Topopah Spring Tuff	300	120 - 1,600	0.13 - 19	0.05 - 0.10
Upper volcanic confining unit Basal vitrophyre of Topopah Spring Tuff, Calico Hills Formation Tuff, and uppermost nonwelded part of Prow Pass Tuff	90 - 330	2.0 - 26	0.02 - 0.26	0.l9 - 0.28
Lower volcanic aquifer Most of Prow Pass Tuff and underlying Bullfrog and Tram Tuffs of Crater Flat Group	370 - 700	1.1 - 3,200	< 0.0037 - 13	0.19 - 0.24
Lower volcanic confining unit Bedded tuffs, lava flows, and flow breccia beneath Tram Tuff	370 - > 750	0.003 - 23	5.5×10^{-6} - 0.11	0.15 - 0.24
Lower carbonate aquifer Cambrian through Devonian limestone and dolomite	N/A[h]	120	0.19	0.003 - 0.05

a. Source: DIRS 100465-Luckey et al. (1996, Table 2 and Figure 7).
b. To convert meters to feet, multiply by 3.2808.
c. Typical thickness ranges for the upper volcanic confining unit, the lower volcanic aquifer, and the lower volcanic confining unit are based on measurements from 13 boreholes. With respect to the lower volcanic confining unit, only one penetrated and showed a unit thickness of about 370 meters (1,200 feet); of the others, about 750 meters (2,500 feet) was the deepest penetration without passing through. Water was detected in the rock unit that elsewhere makes up the upper volcanic aquifer unit in only one of the 13 boreholes. (Beneath the center of Yucca Mountain, the upper volcanic aquifer is above the saturated zone.) The typical thickness shown here for this unit is based on Figure 7 from DIRS 100465-Luckey et al. (1996, Figure 7).
d. To convert square meters to square feet, multiply by 10.764.
e. Source: DIRS 151945-CRWMS M&O (2000, Tables 9.3-4 and 9.3-5, pp. T9.3-6 and T9.3-7).
f. Source: DIRS 151945-CRWMS M&O (2000, pp. 9.3-10 to 9.3-17).
g. Ranges are for means of several hydrogeological subunits.
h. N/A = not available.

and Earth tides (DIRS 151945-CRWMS M&O 2000, p. 9.3-30). In addition, short-term fluctuations in groundwater elevations also have been attributed to apparent recharge events and earthquakes. Water levels in wells have fluctuated by as much as 0.9 meter (3 feet) in response to earthquake events, and confined water pressure deep in wells fluctuated by as much as 2.2 meters (7 feet) in response to those same events. However, the fluctuations are typically of short duration with water levels returning to the pre-earthquake conditions within minutes to a few hours (DIRS 151945-CRWMS M&O 2000, pp. 9.4-20 and 9.4-21). An exception to this occurred in response to earthquakes in the summer of 1992, when water levels in specific wells at Yucca Mountain fluctuated over several months.

At the northern end of Yucca Mountain, the apparent potentiometric surface slopes steeply southward, dropping almost 300 meters (980 feet) in a horizontal distance of about 2 kilometers (1.2 miles) (DIRS 151945-CRWMS M&O 2000, pp. 9.2-46 and 9.3-31). Experts reviewing the data have suggested several credible reasons for this large gradient, including that it results from an undetected geological feature with low permeability, that it is caused by groundwater draining to deep aquifers, or that it is a perched water table being encountered in this area (DIRS 100353-CRWMS M&O 1998, pp. 3-5 and 3-6). However, there are no obvious geologic reasons for the large gradient, and it is still under investigation.

The north-trending Solitario Canyon fault, on the west side of Yucca Mountain, apparently impedes the eastward flow of groundwater in the saturated zone. West of the fault, the water table slopes moderately about 40 meters (130 feet) in less than 1 kilometer (0.6 mile), while east of the fault the water table slopes very gently, changing by only 0.1 to 0.3 meter per kilometer (0.5 to 1.6 feet per mile) (DIRS 151945-CRWMS M&O 2000, pp. 9.3-38 to 9.3-40, and Figure 9.3-15, p. F9.3-15). West of the Solitario Canyon fault groundwater probably flows southward either along the fault or beneath Crater Flat.

The gentle southeastward groundwater gradient east of the Solitario Canyon fault underlies the proposed repository horizon and extends beneath Fortymile Wash and probably farther east into Jackass Flats. This gentle gradient might indicate that the rocks through which the water flows are highly transmissive, that only small amounts of groundwater flow through this part of the system, or a combination of both. This gentle southeastward gradient is a local condition in the regional southward flow of the groundwater.

In an opposing viewpoint about the stability of groundwater levels at Yucca Mountain, DIRS 103180-Davies and Archambeau (1997, pp. 33 and 34) suggests that a moderate magnitude earthquake at the site could cause a southward displacement of the large hydraulic gradient to the north of the proposed repository, resulting in a water table rise of about 150 meters (490 feet) at the site. In addition, that report proposed that a severe earthquake could cause a rise of about 240 meters (790 feet) in the water table, flooding the repository. As part of its study of groundwater flow in the saturated zone, DOE elicited expert opinions on various issues from a panel of five experts in the fields of groundwater occurrence and flow. Among the issues put to the panel were those raised by DIRS 103180-Davies and Archambeau (1997, all). The panel reviewed the Davies and Archambeau paper and received briefings by project personnel and outside specialists. The consensus of the panel was that a rise of the groundwater to the level of the proposed repository was essentially improbable and that changes to the water table associated with earthquakes would be neither large nor long-lived (DIRS 100353-CRWMS M&O 1998, p. 3-14).

Inflow to Volcanic Aquifers at Yucca Mountain. There are four potential sources of inflow to the volcanic aquifers in the vicinity of Yucca Mountain: (1) lateral flow from volcanic aquifers north of Yucca Mountain, (2) recharge along Fortymile Wash from occasional stream flow, (3) precipitation at Yucca Mountain, and (4) upward flow from the underlying carbonate aquifer. The actual and relative amounts of inflow from each source cannot be measured directly on any large-scale basis. However, estimates have been generated based on data collected and tests performed at individual locations and from incorporation of these data into regional- and site-scale models of the unsaturated and saturated zones.

North of Yucca Mountain, the potentiometric surface rises steeply toward probable recharge areas on Pahute Mesa (Figure 3-15) and Rainier Mesa. Chemical data indicate that some recharge to the groundwater has occurred everywhere in the Yucca Mountain vicinity during the past 10,000 years, but that most recharge occurred between 10,000 and 20,000 years ago (based on apparent carbon-14 ages) during a wetter climate (DIRS 151945-CRWMS M&O 2000, p. 9.3-53). From west to east across Yucca Mountain, the age of water in the saturated zone decreases from about 19,000 years to 9,100 years (DIRS 101036-Benson and McKinley 1985, p. 4).

One estimate of the annual recharge along a 42-kilometer (26-mile) segment of Fortymile Wash in the area of Yucca Mountain is about 110,000 cubic meters (88 acre-feet) (DIRS 151945-CRWMS M&O 2000, pp. 7.2-1 and 7.2-2). Much of the recharge occurs during and after heavy precipitation when water flows in the wash. On rare occasions, Fortymile Wash carries water to Jackass Flats and into the Amargosa Desert. After periods of flow in Fortymile Wash during 1983, 1992, 1993, and 1995 water levels in nearby wells rose as a result of infiltration (DIRS 151945-CRWMS M&O 2000, p. 7.2-2). Earlier studies found that shallow water in some wells was younger than water deeper in the wells, indicating that recharge was occurring (DIRS 151945-CRWMS M&O 2000, p. 9.3-53). Paleoclimatic evidence suggests that perennial water was present in Fortymile Wash 50,000 years ago (DIRS 105162-National Research Council 1992, Appendix C, p. 198), and that substantial recharge might have occurred as recently as 7,000 to 15,000 years ago (DIRS 151945-CRWMS M&O 2000, p. 9.3-53).

Recharge to the saturated zone below Yucca Mountain from precipitation is small in comparison to inflow from volcanic aquifers to the north or recharge along Fortymile Wash (see the unsaturated zone discussion). An average net infiltration of 4.7 millimeters (0.2 inch) over a 4.7-square-kilometer (1.8-square-mile) repository footprint would produce a quantity of recharge about 20 percent of the estimated annual recharge along the nearby 42-kilometer (26-mile) segment of Fortymile Wash.

Monitoring well data collected during the site characterization effort have shown that the potentiometric surface of the carbonate aquifer (that is, the level to which water rises in wells tapping this aquifer), at least in the immediate vicinity of Yucca Mountain, is higher than the water level in the overlying volcanic aquifer. Based on this and other considerations, studies suggest that, provided structural pathways exist, the lower carbonate aquifer might provide upward flow to the volcanic aquifer beneath the proposed level of the repository and farther south. The amount of inflow, if it occurs, is not known.

Outflow from Volcanic Aquifers at and Near Yucca Mountain. Pathways by which water might leave the volcanic aquifers in the Yucca Mountain vicinity include (1) downgradient movement into other volcanic aquifers and alluvium in the Amargosa Desert, (2) downward movement into the carbonate aquifer (though evidence indicates that this does not occur), and (3) upward movement into the unsaturated zone. In addition, water is pumped from wells for a variety of uses, as described in Section 3.1.4.2.1. With the exception of well withdrawals, the actual and relative amounts of outflow from each source are not known.

The regional slope of the potentiometric surface indicates that much of the groundwater flowing southward beneath Yucca Mountain discharges about 60 kilometers (37 miles) to the south at Alkali Flat (Franklin Lake Playa) and in Death Valley. Death Valley, more than 80 meters (260 feet) below sea level, is the final sink for surface water and groundwater in the Death Valley regional groundwater flow system (Figure 3-13); as such, water leaves only by evapotranspiration. Therefore, the pathway for groundwater beneath Yucca Mountain, as indicated by the potentiometric surface, is southerly where it traverses portions of the volcanic aquifers before encountering the basin-fill alluvium and carbonate rock that underlie the Amargosa Desert.

Outflow from the volcanic aquifers into the underlying carbonate aquifer might occur, but direct evidence for this does not exist. Studies suggest that the steeply sloping potentiometric surface at the north end of Yucca Mountain could be explained by a large outflow from the volcanic aquifers to the carbonate aquifer. However, in the vicinity of Yucca Mountain, data available on the potentiometric head of the carbonate aquifer indicate that the opposite condition (that is, outflow from the carbonate aquifer up to the volcanic aquifer) is more likely.

The third possible pathway of outflow from the volcanic aquifer (that is, upward movement to the unsaturated zone), if present, has not been quantified. However, consistent with the above discussion of net infiltration, DOE believes that there is a net downward movement of water in the unsaturated zone in the vicinity of Yucca Mountain.

Use. Two wells, J-12 and J-13 (shown in Figure 3-20), are part of the water system for site characterization activities at Yucca Mountain. These are the nearest production wells to Yucca Mountain and they support water needs for Area 25 of the Nevada Test Site and for Exploratory Studies Facility activities. Both of these wells withdraw groundwater from the Jackass Flats hydrographic area, as listed in Table 3-11. Groundwater has also been pumped from the Jackass Flats area from various boreholes for hydraulic testing, and most recently from the C-well complex, which consists of three separate wells grouped in an area just east of the South Portal Development Area (DIRS 100465-Luckey et al. 1996, Figure 17). In addition, water has been pumped occasionally from borehole USW VH-1 (also designated CF-2) in support of Yucca Mountain characterization activities. But the volume pumped from this well, which is in the Crater Flat hydrographic area, is small (DIRS 100465-Luckey et al. 1996, p. 70).

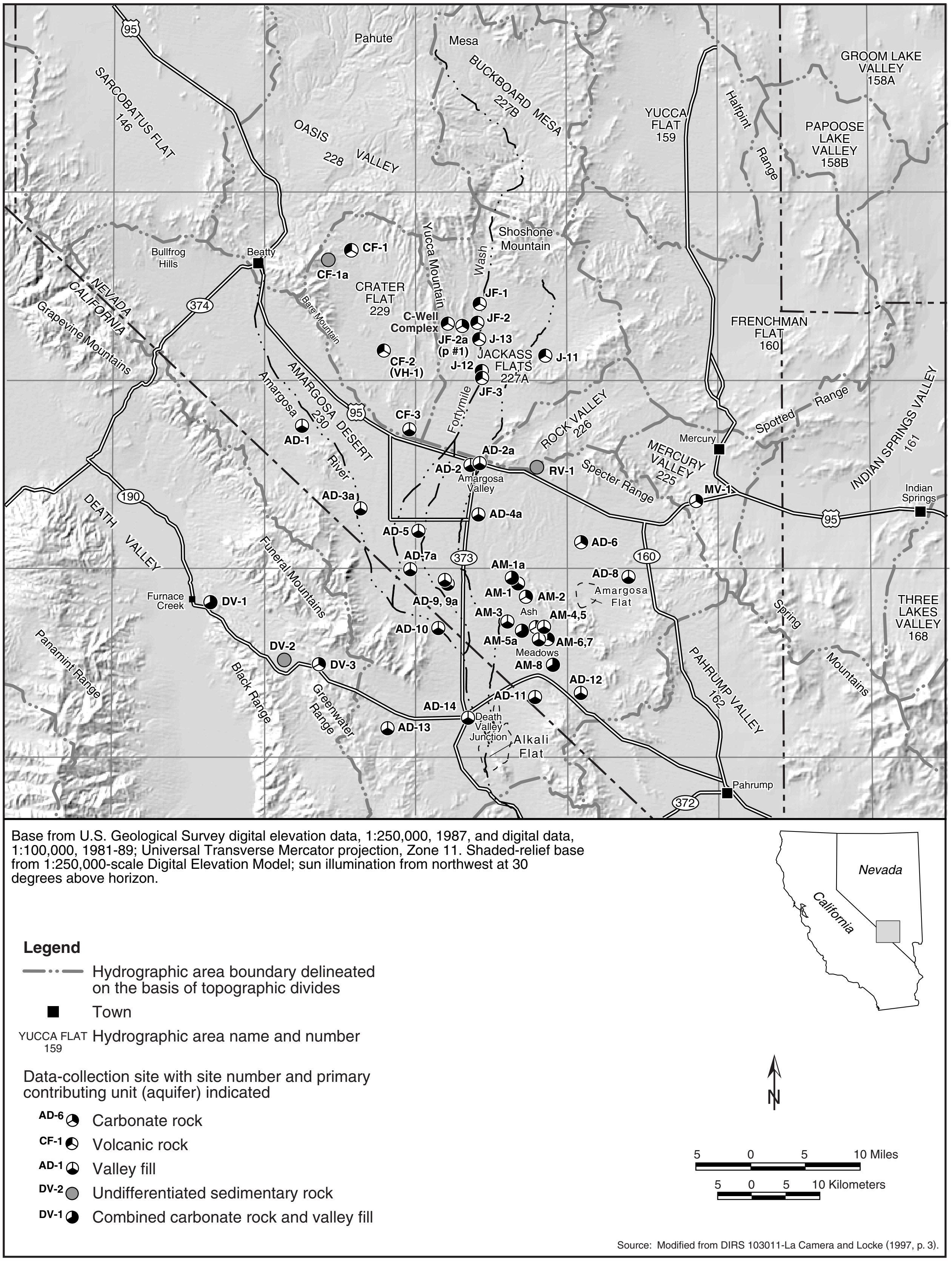


Figure 3-20. Selected groundwater data-collection sites in the Yucca Mountain region.

The Yucca Mountain Site Characterization Project has received water appropriation permits (Numbers 57373, 57374, 57375, and 57376) from the State of Nevada for wells J-12, J-13, VH-1 (also known as CF-2), and the C-Well complex (Numbers 58827, 58828, and 58829), and a Potable Water Supply permit (NY-0867-12NCNT) for the distribution system. The permits allow a maximum pumping rate of about 0.028 cubic meter (1 cubic foot) a second, with a maximum yearly withdrawal of about 530,000 cubic meters (430 acre-feet) (DIRS 151945-CRWMS M&O 2000, p. 9.5-3 and 9.5-4, and Table 9.5-3, p. T9.5-3). The permit limits apply to site characterization water use. Table 3-16 lists historic and projected water use from wells J-12 and J-13 from 1992 to 2005 for the Exploratory Studies Facility and Concrete Batch Plant, and from the C-Wells, which is pumped and then reinjected as part of aquifer testing. It also lists the total amount of water pumped from wells J-12 and J-13 for both Yucca Mountain and the Nevada Test Site. The difference between the quantities pumped from wells J-12 and J-13 for Yucca Mountain activities and the total withdrawals from these wells represents the quantities used for Nevada Test Site activities in the area. The water-use projections in Table 3-16 are through the end of site characterization activities; Section 4.1.3 discusses water demand projections for the proposed repository.

Table 3-16. Water withdrawals (acre-feet)[a] from wells in the Yucca Mountain vicinity.

Year	J-12 and J-13 Yucca Mountain characterization[b]	J-12 and J-13 total withdrawals[c]	C-wells[b]
1992	18	120	0
1993	80	210	0
1994	75	280	0
1995	94	260	19
1996	66	220	180
1997	63	150	190
1998	63[d]	N/A[e]	190[f]
1999	63	N/A	N/A
2005	63	N/A	N/A

a. To convert acre-feet to cubic meters, multiply by 1233.49.
b. Source: DIRS 104988-CRWMS M&O (1999, p. 4).
c. Source: DIRS 103171-Clary et al. (1995, p. 660); DIRS 101486-Bauer et al. (1996, p. 702); DIRS 103090-Bostic et al. (1997, p. 592); DIRS 103082-Bonner et al. (1998, p. 606); DIRS 103283-La Camera, Locke, and Munson (1999, all); withdrawals for 1992 and 1993 were estimated from figures in DIRS 103011-La Camera and Locke (1997, p. 51).
d. Assumed to remain constant from 1997 through 2005.
e. N/A = not available.
f. Assumed to remain constant from 1997 to 1998.

The U.S. Geological Survey, in support of Yucca Mountain characterization efforts and in compliance with the State permits, has kept records of the amount of water pumped from the J-12 and J-13 wells and of measured water elevation levels in those and other wells in their immediate area since 1992 (DIRS 103011-La Camera and Locke 1997, pp. 1 and 2). One of the objectives of keeping these records is to detect and document changes in groundwater resources during the Yucca Mountain investigations. Therefore, the Survey effort included the collection of historic water elevation data to establish a baseline. Results from these efforts have been documented in annual reports. The report for 1997 (DIRS 103283-La Camera, Locke, and Munson 1999, all) includes a summary of 1996 results and detailed results for 1997. Table 3-17 summarizes the changes observed in median groundwater elevations in seven wells in Jackass Flats. The second column of the table identifies the historic or baseline elevation for each well against which the annual median values are being compared. In addition, the table lists the average deviation of measured water levels during the period from which the baseline was generated.

Table 3-17. Differences between annual median elevations and baseline median elevations.[a]

Well	Baseline elevations: Median (meters[c] above sea level)	Baseline elevations: Average deviation about the median (centimeters)	Difference (in centimeters[b]) baseline: 1992	1993	1994	1995	1996	1997
JF-1	729.23	± 6	–3	0	–6	0	–6	–3
JF-2	729.11	± 9	+3	0	+3	+9	0	–3
JF-2a[d]	752.43	± 12	0	+6	+12	+15	+21	+27
J-13	728.47	± 6	–3	–3	–9	–6	–12	–12
J-11	732.19	± 3	0	0	+3	+6	+6	+12
J-12	727.95	± 3	0	0	–3	–3	–9	–9
JF-3	727.95	± 3	N/A[e]	N/A	–6	–6	–9	–9

a. Source: DIRS 103283-La Camera, Locke, and Munson (1999, Table 10).
b. To convert centimeters to inches, multiply by 0.3937.
c. To convert meters to feet, multiply by 3.2808.
d. Well JF-2a is also known as UE-25 p#1, or P-1.
e. N/A = not available.

The elevation changes listed in Table 3-17 are different from the short-term fluctuations described above that are a response to changes in barometric pressure and Earth tides. The differences in comparison of annual median values should indicate water level trends, if there are any. The data show that a decline in groundwater elevation has been seen in some, but not all, of the local wells. Specifically, the data show the following:

- Two wells, JF-1 and JF-2, stayed within the band of elevations characteristic of the baseline data.
- Two wells, JF-2a (also known as UE-25 p#1, or P-1) and J-11, indicated elevation increases of 15 and 9 centimeters (about 5.9 and 3.5 inches), respectively, above the band of elevations characteristic of the baseline data (and even higher above the median of the baseline data as listed in the table).
- Three wells, J-13, J-12, and JF-3, each indicated an elevation decrease of 6 centimeters (about 2.4 inches) below the band of elevations characteristic of the baseline data (and even further below the median of the baseline data as listed in the table).

In its discussion of groundwater levels, the U.S. Geological Survey (DIRS 103011-La Camera and Locke 1997, p. 22) indicated that monitoring of water levels in the seven wells should continue to see if additional decreases occur and if they can be correlated to periods of withdrawal. In regard to overall groundwater levels in the Jackass Flats area, the data do not appear to show any definitive trend in elevation change, either up or down. However, the three wells showing a water decline are either being pumped (J-12 and J-13) or, in the case of JF-3, are close to a production well. Of the two wells (JF-2a and J-11) showing water-level increases, one (JF-2a) penetrates the lower carbonate aquifer and the other, though penetrating a volcanic aquifer, is farthest from the production wells of any shown on the table. Pumping from the volcanic aquifer production wells would be unlikely to affect either of these wells. There is some speculation that the consistent water-level increase over time in well JF-2a might indicate that it has not yet reached an *equilibrium* elevation.

Saturated Zone Groundwater Quality. Groundwater quality for the aquifers beneath Yucca Mountain was addressed by the Geological Survey sampling and analysis effort described above for regional groundwater quality. This effort included the collection and analysis of samples from three wells in the Jackass Flats area (including J-12 and J-13); the results indicated that the concentrations of dissolved substances in local groundwater were below the numerical criteria of the primary drinking water standards set by the Environmental Protection Agency for public drinking water systems (DIRS 104828-Covay 1997, all). However, samples from each of the wells exceeded the secondary standard for fluoride, as they did for a proposed standard for radon. Both of these constituents occur naturally in the rock through which the groundwater flows. Overall, local groundwater quality is generally good.

Investigations of the chemical and mineral composition of groundwater at Yucca Mountain have provided an indication of the differences between the aquifers beneath the site. The chemical composition of groundwater depends on the chemistry of the recharge water and the chemistry of the rocks through which the water travels. Water in the volcanic aquifers and confining units at Yucca Mountain has a relatively dilute sodium-potassium-bicarbonate composition that probably results from the *dissolution* of volcanic tuff (Table 3-18). The chemistry of water from the lower carbonate aquifer is very different (a generally more concentrated calcium-magnesium-bicarbonate composition), which would be expected from water traveling through and dissolving carbonate rock (Table 3-18).

Table 3-18. Water chemistry of volcanic and carbonate aquifers at Yucca Mountain (milligrams per liter).[a]

Chemical constituent	Chemical composition: Volcanic aquifers[b]	Chemical composition: Lower carbonate aquifer[c]
Calcium	1.4 - 37	100
Magnesium	< 0.01 - 10	39
Potassium	1.1 - 5.6	12
Sodium	38 - 120	150
Bicarbonate	110 - 282	569
Chloride	5.5 - 13	28
Sulfate	16 - 45	160
Silica	40 - 57	41

a. Source: DIRS 101036-Benson and McKinley (1985, Table 1, p. 5).
b. Based on samples from 14 wells.
c. Based on samples from one well.

As part of the Yucca Mountain project, well and spring monitoring activities performed during 1997 aided the establishment of a baseline for radioactivity in groundwater near the site of the proposed repository (DIRS 104963-CRWMS M&O 1998, all). The quarterly sampling included six wells and two springs that were selected to ensure that at least two were representative of each of the three general aquifers (carbonate, volcanic, and alluvial) in the region. Samples were analyzed for gross alpha, gross beta, total uranium, and concentrations of selected beta and gamma-emitting radionuclides. Table 3-19 lists the results from this monitoring as average values from the quarterly sampling events for each well or spring. The table lists the location of each well or spring, including the data collection site designations shown on Figure 3-20, the contributing aquifer, and a comparison, if applicable, to *Maximum Contaminant Levels* established by the Environmental Protection Agency for water supplied by public drinking water systems. As indicated in the table, the sites sampled include locations outside the Alkali Flat-Furnace Creek groundwater basin in which Yucca Mountain is located. The Cherry Patch location is in the Ash Meadows groundwater basin and Crystal Pool and Fairbanks Spring are on the border between the two basins, but are fed by flow through Ash Meadows. The location variety supports area comparisons as well as comparisons between the different contributing aquifers.

Table 3-19 indicates that Maximum Contaminant Levels for combined radium-226 and radium-228 and for gross alpha were not exceeded by the average values from any of the sampling sites or by the maximum values reported for those parameters (DIRS 104963-CRWMS M&O 1998, pp. 12 to 21). The samples were analyzed for other beta- or gamma-emitting radionuclides, specifically tritium, carbon-14, chlorine-36, nickel-59, strontium-89, strontium-90, technetium-99, iodine-129, and cesium-137. The table does not list the results for these parameters because they are below minimum detectable activity (DIRS 104963-CRWMS M&O 1998, p. 13). As a conservative measure, however, DOE used the values reported by the laboratory to calculate dose contributions (DIRS 104963-CRWMS M&O 1998, Appendix F). Water from each sampling location was shown to have exposure values well below the 4-millirem-per-year total body (or any internal organ) dose limit set as the Maximum Contaminant Level for beta- or gamma-emitting radionuclides.

Table 3-19. Results of 1997 groundwater sampling and analysis for radioactivity.[a]

Site name and location description[b]	Contributing aquifer	Average combined radium-226 and -228 (picocuries per liter)	Average gross alpha (picocuries per liter)	Average total uranium[c] (micrograms per liter)	Average gross beta (picocuries per liter)	Average radon-222 (picocuries per liter)
J-12 and J-13[d] Fortymile Wash, SE of Yucca Mtn.	Volcanic	0.32±0.24	BDL[e]	0.52±0.03	6.04±0.60	384
C-3 (C-well complex) By South Portal, SE of Yucca Mtn.	Volcanic	0.58±0.36	1.34±1.05	1.04±0.09	3.59±0.76	763
Crystal Pool (Spring) (AM-5a) Ash Meadows	Carbonate/ alluvial[f]	0.93±0.20	BDL	2.64±0.23	14.0±1.28	447
Fairbanks Spring (AM-1a) Ash Meadows	Carbonate/ alluvial	0.80±0.36	BDL	2.23±0.19	11.1±1.17	279
Nevada Department of Transportation Well (AD-2a) Amargosa Valley	Alluvial	0.32±0.33	BDL	2.55±0.22	5.95±0.93	612
Gilgans South Well (AD-9a) Amargosa Desert	Alluvial	0.19±0.31	BDL	0.63 ± 0.05	9.14±0.97	600
Cherry Patch Well (AD-8) NE of Ash Meadows	Alluvial	0.22±0.33	9.19±4.35	13.1 ± 1.16	18.7±1.65	504
Drinking water Maximum Contaminant Levels[g]		5	15	NA[h]	NA	300 (proposed)

a. Source: DIRS 104963-CRWMS M&O 1998, pp. 12 to 21) for all but radon-222 data; DIRS 104828-Covay (1997, Table 4) for radon data.
b. Figure 3-20 shows the locations of the wells.
c. To convert total uranium concentrations in micrograms per liter to picocuries per liter, multiply by 0.68 (DIRS 104963-CRWMS M&O 1998, p. 15).
d. Average of data presented for Well J-12 and Well J-13.
e. BDL = below detection limit.
f. Alluvium is also identified as valley fill in DIRS 151945-CRWMS M&O (2000, p. 9.2-23).
g. Drinking water Maximum Contaminant Levels are set by the Environmental Protection Agency in 40 CFR Part 141.
h. NA = not applicable.

There is no indication that DOE activities at the Nevada Test Site have contaminated the groundwater beneath Yucca Mountain. This is consistent with studies performed on the Nevada Test Site. DIRS 103411-Nimz and Thompson (1992, all) documented about a dozen instances in which radionuclides have migrated into the groundwater from areas of nuclear weapons testing at the Nevada Test Site in 40 years. The maximum distance of tritium migration is believed to be several kilometers; less mobile radioactive constituents, which include a wide variety of isotopes (DIRS 101811-DOE 1996, pp. 4-126 to 4-129), have migrated no more than about 500 meters (1,600 feet). There has, however, been recent evidence of plutonium migration from one below-groundwater test at Pahute Mesa.

Groundwater monitoring results indicate plutonium has migrated at least 1.3 kilometers (0.8 mile) from this site in 28 years and is apparently associated with the movement of very small particles called colloids (DIRS 103282-Kersting et al. 1999, p. 56). None of the nuclear testing occurred in Area 25 where the Yucca Mountain Repository facilities would be. However, the flow of groundwater from areas on Pahute and Buckboard Mesas where DOE conducted 81 and 2 nuclear tests, respectively, could be to the south toward Yucca Mountain. The distance is about 40 kilometers (25 miles) to Pahute Mesa and about 30 kilometers (19 miles) to Buckboard Mesa (Figure 3-20). Because of these distances, there is no reason to believe that radionuclides from nuclear tests could migrate as far as Yucca Mountain during the active life (construction, operation and monitoring, and closure phases) of the repository, with the possible exception of tritium. Conservative modeling performed by DOE at the Nevada Test Site (DIRS 103021-DOE 1997, pp. ES-27 to ES-29, and ES-36) shows that tritium, moving with little or no attenuation in groundwater other than decay, could move to locations at or near Nevada Test Site boundaries in tens of years. However, the same study reports that monitoring has not shown tritium to be moving as rapidly as predicted when using the conservative assumptions of the model. In addition, the flow paths from the underground nuclear testing areas, as predicted in this study, do not intersect groundwater beneath Yucca Mountain. Chapter 8 discusses the potential for long-term migrations of radionuclides to result in cumulative radiation from nuclear testing contamination eventually migrating through the groundwater system and joining groundwater beneath the repository.